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PYROELECTRIC DETECTORS

Eugene E. Haller, J. Beeman and W.L. Hansen

Lawrence Berkeley Laboratory and University of California at Berkeley
1 Cyclotron Road, Berkeley, California 94720

and

G. Scott Hubbard and R.E. McMurray, Jr.

NASA Ames Research Center, Moffett Field, Califonia 94035

The multi-agency, long-term Global Change programs, and specifically NASA's Earth Observing system, will require some new and advanced photon detector technology which must be specifically tailored for long-term stability, broad spectral range, cooling constraints, and other parameters. Whereas MCT and GaAs alloy based photovoltaic detectors and detector arrays reach most impressive results to wavelengths as long as 12 μm when cooled to below 70 K, other materials, such as ferroelectrics and pyroelectrics, appear to offer special opportunities beyond 12 μm and above 70 K. These materials have found very broad use in a wide variety of room temperature applications. Little is known about these classes of materials at sub-room temperatures and no photon detector results have been reported. From the limited information available we conclude that the room temperature values of $D^* \gtrsim 10^9$ cm $Hz^{1/2}/W$ may be improved by one to two orders of magnitude upon cooling to temperatures around 70 K Improvements of up to one order of magnitude appear feasible for temperatures achievable by passive cooling.

The flat detector response over a wavelength range reaching from the visible to beyond 50 μm, which is an intrinsic advantage of bolometric devices, makes for easy calibration. The fact that these materials have not been developed for reduced temperature applications makes ferro- and pyroelectric materials most attractive candidates for serious exploration.

PYROELECTRIC MATERIALS AND DETECTORS

Eugene E. Haller, J. Beeman and W.L. Hansen
Lawrence Berkeley Laboratory
and University of California at Berkeley
1 Cyclotron Road, Berkeley, CA 94720

and

G. Scott Hubbard and R.E. McMurray, Jr.
NASA Ames Research Center
Moffett Field, CA 94025

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INTRODUCTION

- Global Change programs, including NASA's Earth Observing System (EOS) require a variety of detectors which can:
  - cover a broad spectral range from the visible to the LWIR and beyond
  - operate at temperatures $\geq$ 65 K in actively cooled instruments
  - operate at temperatures $\geq$ 120 K in passively cooled instruments
  - have long term stability
  - utilize simple and reliable calibration procedures
  - be integrated into imaging arrays
- Thermal detectors, including bolometers and pyroelectric detectors, fulfill a large number of the above requirements
- Operation of thermal detectors in the above given temperature ranges has not been explored in detail

THERMAL DETECTORS

- **Basic parameters and equations:**

  – Heat capacity $H = dE/dT$ $(J\,K^{-1})$

  – Heat conductance $G = dP/dT$ $(W\,K^{-1})$

  with E = total energy
  P = power
  T = temperature

  – Thermal circuit:

$$\eta P = H\frac{d\theta}{dt} + G\theta$$

with η = quantum efficiency (fraction of incident power absorbed by detector)

θ = average temperature rise of the detector i.e. $T_D = T_o + \theta$

t = time

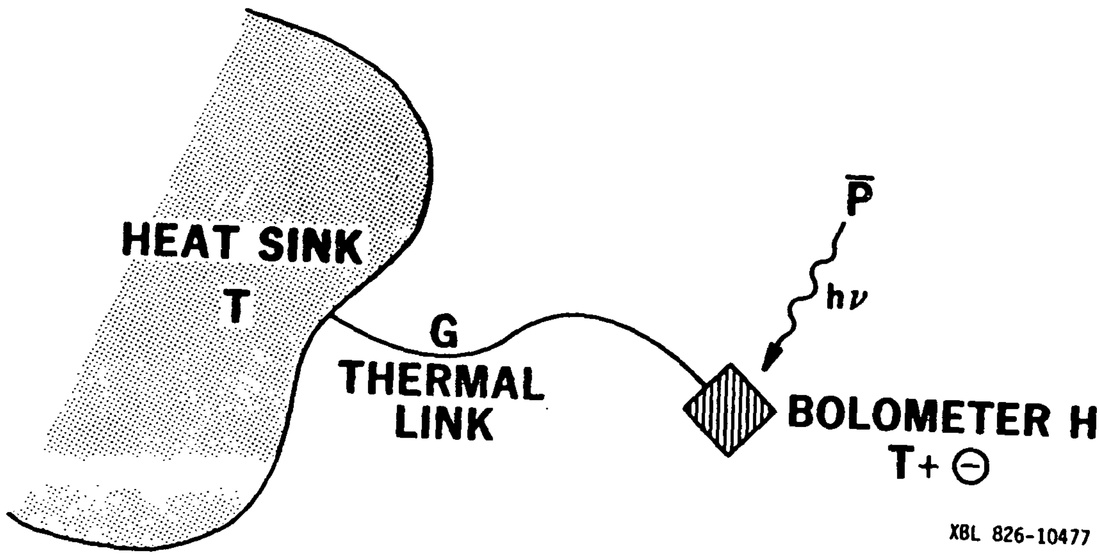
for a radiation source with

$$P = P_o + P_\omega e^{i\omega t}$$

one finds:

$$\theta_\omega = \eta\, P_\omega \left(G^2 + \omega^2 H^2\right)^{-1/2}$$

$$\varphi = \tan^{-1}\left(\omega H / G\right)$$



- thermal time constant

  $\tau_T = H/G$

- minimum value of G:

  $G_{min} = G_{radiative} = 4\,A\eta\,\sigma\,T^3$

  with A = detector area
  σ = Stefan-Boltzmann constant
  ($= 5.67 \times 10^{-12}$ W cm^{-2} K^{-4})

- **Background limited performance:**

  - Power fluctuation through thermal link:

    $\Delta W_T = (4kT^2G)^{1/2}$

  - Minimum detectable signal power P_N:

    $\eta\,P_N = \Delta W_T = (16A\,\eta\,\sigma\,kT^5G)^{1/2}$

    or $P_N = (16A\,\sigma\,kT^5/\eta)^{1/2}$

    $P_N = (16A\,\sigma\,kT^5)^{1/2} = 5\times10^{-10}$ W (at T=300 K)

    (for 1 Hz bandwidth, A = 1 cm^2,
    2π field of view and $\eta = 1$)

    P_N (T=200 K) = 2×10^{-11}W

    P_N (T=100 K) = 3.5×10^{-12}W

    (equivalent to $D^* = 2.86\times10^{11}$cm $\sqrt{Hz}$ W^{-1})

PYROELECTRIC DEVICES

- **Pyroelectric devices are thermal detectors**
- **No fundamental limits for wavelength of photons to be detected**
- **Flat wavelength response makes for easy calibration**

- **Figures of merit:**
  - Pyroelectric coefficient:

    $p = dP_S/dT$

    P_S = spontaneous polarization
  - pyroelectric current

    $I_p = Ap\, dT/dt$

  with:

  c = volume specific heat

  d = thickness of the detector
  - current responsivity:

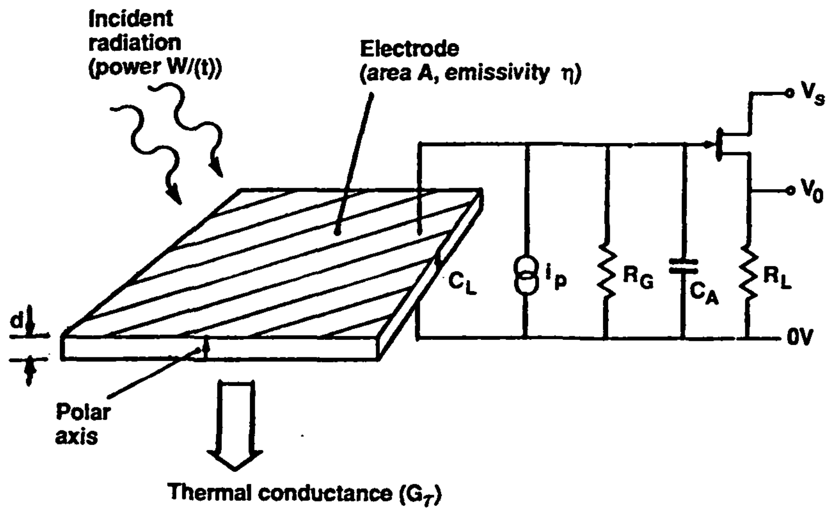
$$R_i = \frac{I_p}{P_\omega} = \frac{\eta p A \omega}{G\left(1+\omega^2\tau_T^2\right)^{1/2}}$$

at low frequencies $\left(\omega \ll \tau_T^{-1}\right)$

$$R_i \propto \omega$$

at high frequencies $\left(\omega \gg \tau_T^{-1}\right)$

$$R_i = \frac{\eta p A}{H} = \frac{\eta p}{c d}$$



Schematic diagram of a pyroelectric radiation detector.

(From R. W. Whatmore, Rep. Prog. Phys. 49, 1335 (1986), Fig. 5)

- voltage responsivity:

$$R_v = \frac{i_p}{Y P_\omega} = \frac{R\,\eta\,p\,A\,\omega}{G\left(1+\omega^2\tau_T^2\right)^{1/2}\left(1+\omega^2\tau_E^2\right)^{1/2}}$$

with $Y = R^{-1} + i\omega C$; R = total input resistance,
C = total input capacitance, $\tau_E = R\,C$

- at high frequencies $\left(\omega \gg \tau_T^{-1}, \tau_E^{-1}\right)$:

$$R_v = \frac{\eta\,p}{c\,\varepsilon\,\varepsilon_o\,A\,\omega}$$

Pyroelectric material figure of merit:

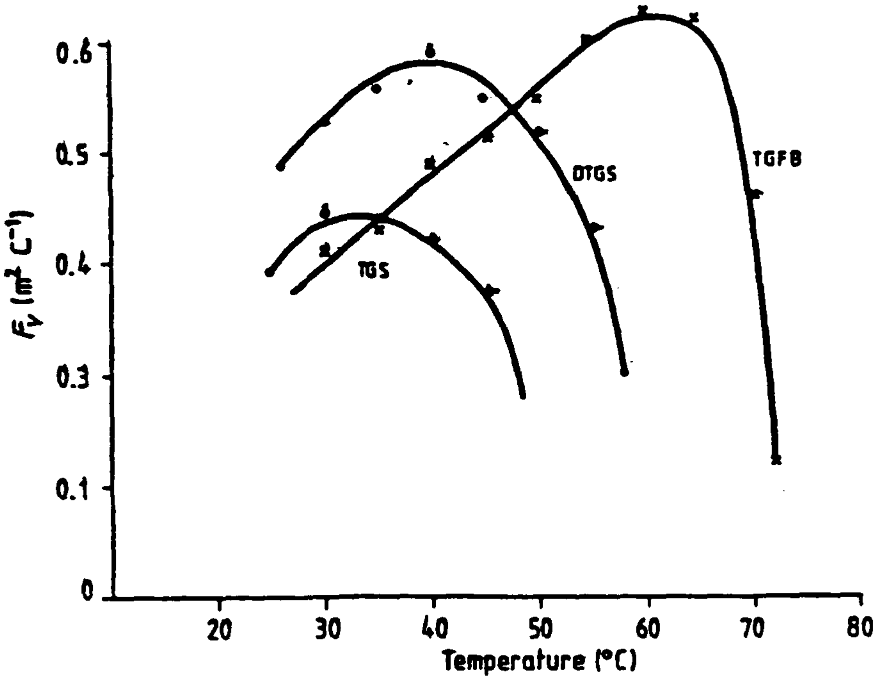
$$F_v = p / c\,\varepsilon\,\varepsilon_o$$

(The larger F_V, the closer we can approach D_{BLIP})

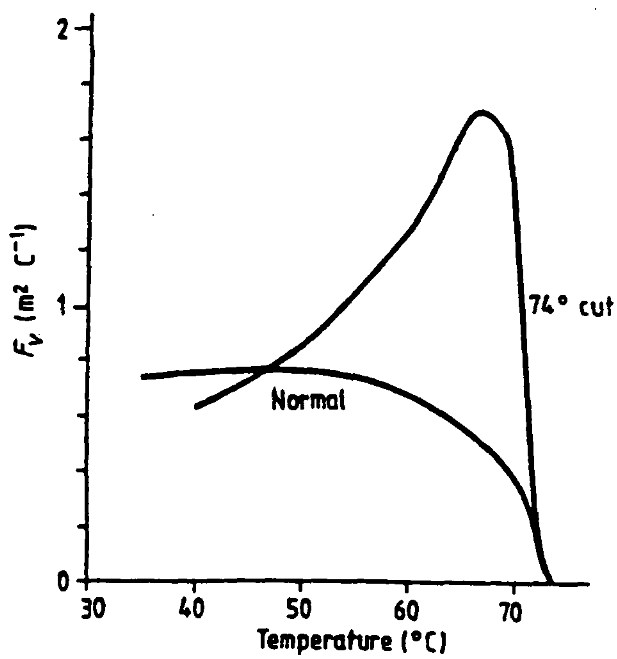
Pyroelectrics have a relative dielectric constant ε which is temperature dependent. With a DC electric field E applied one finds:

$$p = \left.\frac{dD}{dT}\right]_E = \left.\frac{dP_s}{dT}\right]_E + \left.\frac{d\varepsilon}{dT}\right]_E E$$

Of special interest are ferroelectrics operated above T_C. Dielectric losses approach zero in this range.



Temperature dependence of the merit figure F_V for some members of the TGS family.



Temperature dependence of F_V in DTGFB at a normal cut and in a cut perpendicular to a direction that forms an angle of 74° with the pyroelectric axis (after Shaulov 1981).

(after R.W. Whatmore, Rep. Prog.Phys. 49, 1335 (1986), Figs. 15 (upper) and Fig. 16 (lower))

MATERIALS PROPERTIES

- **Triglycine sulphate family (TGS) at room temperature:**

  p: 5.5 – 7.0 ($\times 10^{-4} C m^{-2} K^{-1}$)

  ε: 30 – 60

  dielectric loss tangent at 1 kHz: 0.02 (typical)

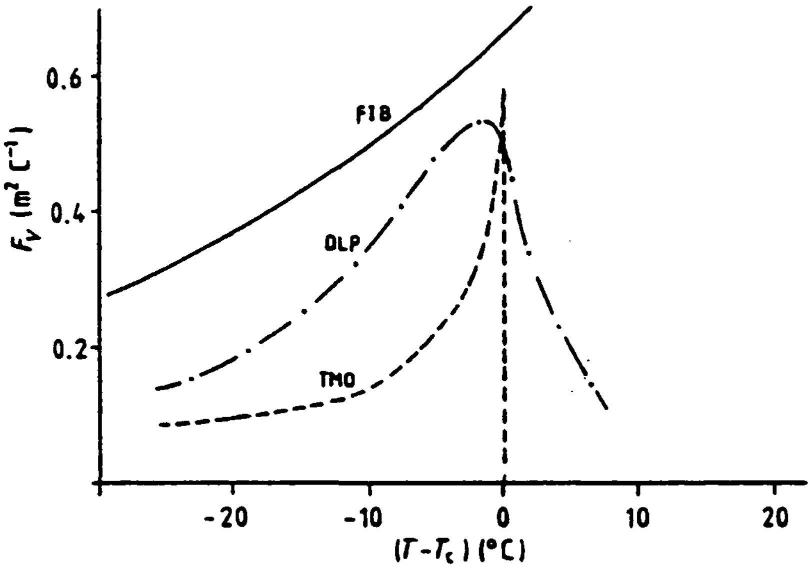
  c: 2.5×10^{6} J cm^{-3} K^{-1}

  F_V: 0.4 – 0.6 m^2 C^{-1}

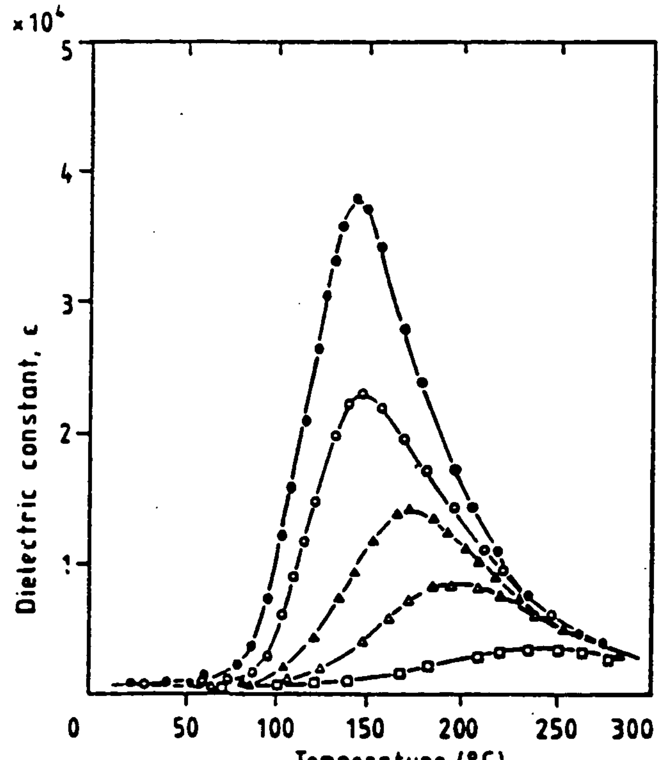
  – for room temperature application the TGS family offers the best set of materials properties

- **Polar materials at 25°C**

	F_V: (m^2 C^{-1})
Polyvinilidyne fluoride (PVDF)	0.1
Li TaO_3	0.17
$Sr_xBa_{1-x}Nb_2O_6$ (0.25 < x < 0.75)	0.07
Lead zirconates (PZ)	0.06
Improper ferroelectrics	≤ 0.5



Temperature dependence of F_V in selected improper ferroelectrics (after Shaulov *et al* 1980).



Effect of DC bias on dielectric constant as a function of temperature in $Pb(Zn_{1/3}Nb_{2/3})O_3$ (after Yokomizo *et al* 1970). ●, zero bias; ○, 3 kV cm^{-1}; ▲, 7 kV cm^{-1}; △, 11 kV cm^{-1}; □, 25 kV cm^{-1}.

(after R.W. Whatmore, Rep. Prog. Phys. 49, 1335 (1986), Fig. 22 (upper) and Fig. 23 (lower))

- **Pyroelectrics under DC bias**

  - above T_C we find:

    $$p = \left.\frac{d\varepsilon}{dT}\right]_E E$$

  - T_C can be engineered through alloy formation:

    e.g. $\alpha\, Ta_x\, Nb_{1-x}\, O$

  - at temperatures near the zero field T_C, both

    $\frac{dP_s}{dT}$ and $\frac{d\varepsilon}{dT}$ increase with the applied DC

  - dielectric losses above T_C vanish

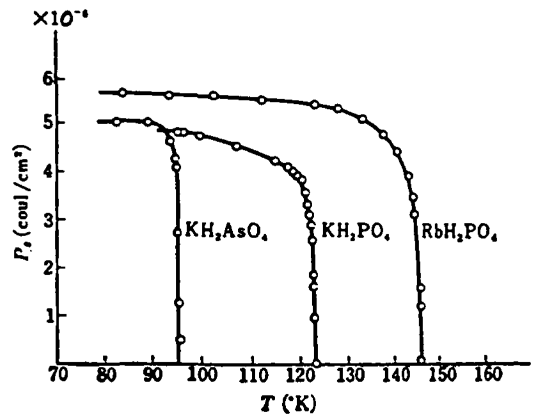
- **Pyro and Ferroelectric Materials with $100\ K < T_C < 200\ K$**

  - KDP (Potassium dihydrogen phosphate) family:

    T_C depends on the specific chemical composition

  - KTN (Potassium tantalum niobium oxide) family:

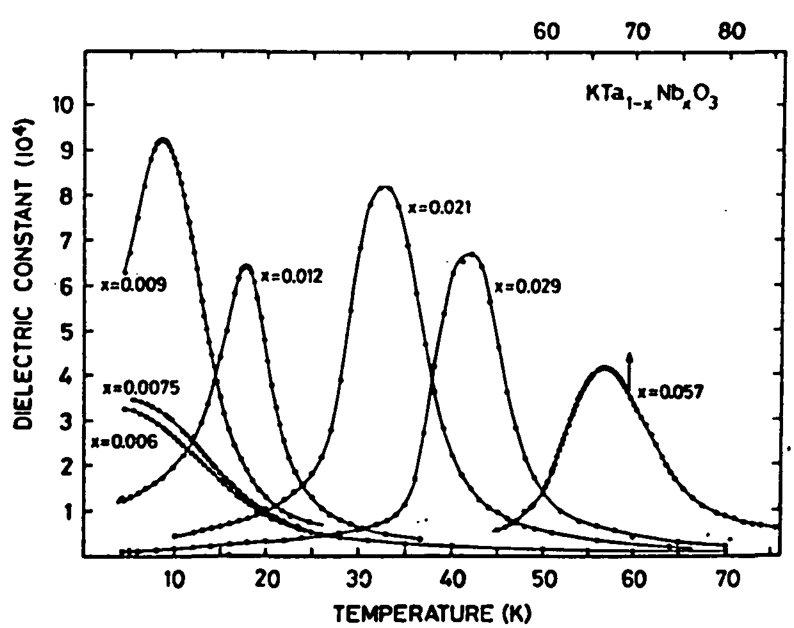
    T_C can be adjusted to any given temperature between 0 and 500 K by alloying. This materials system is fully miscible.



Temperature dependences of the spontaneous polarization of KH_2PO_4 type ferroelectrics.

(From T. Mitsui et al., "An Introduction to the Physics of Ferroelectrics", Gordon and Breach 1984)

D. RYTZ, A. CHÂTELAIN, AND U. T. HÖCHLI



Temperature dependence of the static dielectric constant ϵ with concentration x as a parameter. The data were obtained by a conventional bridge technique at 1 kHz. The temperature was changed at a rate of no more than 0.5 K/min. Note the change on the temperature scale for $x = 0.057$.

(From D. Rytz et al., Phys. Rev. B27, 6830 (1983), Fig. 3)

SUMMARY

- Bolometric detection has specific advantages such as:
  - response to photon power unlimited by the photon wavelength
  - ease of calibration
- Background limited D^* (100 K)

  $= 2.86 \times 10^{11}$ cm $\sqrt{Hz}$ W^{-1}; this appears sufficient for a number of remote sensing applications, possibly including EOS LWIR focal plane arrays
- Passively cooled systems can make use of pyro- and ferroelectrics
- The critical temperature of pyroelectrics near which highest performance is achieved, can be engineered through alloying
- Low temperature pyro- and ferroelectrics offer great potential for exploratory research